Hurricane Andrew

The 1992 hurricane allowed scientists to assess damage and consider long-term consequences to well-studied ecosystems

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Hurricane Andrew was intense. The National Weather Service reported that after landfall at 5 A.M. on 24 August 1992, the eye passed over South Florida in an almost due westerly direction. The atmospheric pressure fell to 922 millibars, and sustained winds reached 242 km/hr. Andrew hit near the time of high tide, pushing up the water level—the storm surge—to a local maximum of 5.2 m above normal levels on the east coast of Florida. Moving over the peninsula at a rate of 50 km/hr, it caused a smaller storm surge of 4.6 m on the west coast.

Two rain gauges that survived the storm recorded approximately 5 cm of rain, making Andrew a relatively dry hurricane. In this region, less severe storms have dropped more than 12 cm of rain, and rainfall in particularly wet storms can be more than a meter. Hurricane Andrew's path over land was only approximately 100 km long, and it partially or completely defoliated vegetation across only a 50-kilometer-wide swathe. Nonetheless, the storm's eye crossed three National Park Service sites: Biscayne National Park, Everglades National Park, and Big Cypress National Preserve. These three areas (henceforth called parks) encompass an unusual diversity of ecosystems. In this and the four articles that follow, we discuss the effects of Andrew on these ecosystems.

Researchers are guardedly optimistic that the ecosystems will recover

Andrew caused extensive damage to the facilities in the parks and devastated the community of Homestead. To assess the biological damage, the National Park Service convened a group of scientists from around the nation to work with local personnel. The assessment group divided into marine, terrestrial, and freshwater teams. They began work on 15 September and worked for ten days to provide a fast and inevitably limited survey of Andrew's effects. Scientists had previously studied various environmental features in the three parks, allowing the team to re-survey sites with known histories. The teams' reports clearly show the importance of the existing long-term studies as well as the gaps in their coverage. This introductory article is based largely on the teams' joint report (Davis et al. 1994), with information from the extensive mangrove forests incorporated from a separate paper (Smith et al. page 256 this issue). All four of the articles that follow stress the cursory nature of their short assessment. For the long-term effects, we can only speculate based on prior experience.

The biotic environments of South Florida

That a hurricane can hit three parks in two hours testifies to the diversity and national uniqueness of South Florida ecosystems (Figure 1). Consider a typical transect starting off the east coast of South Florida and working westward. From 5 to 8 km seaward of the east coast, the sea floor rises to a thin band of barrier reefs. Landward of the reefs is an extensive shallow water bank with coral reefs and seagrass beds. The east coast, beginning north of Miami, is bordered by a string of islands, called keys, that extend southward and then bend westward to Key West. The southernmost keys are primarily covered with mangrove forests. Between the keys and the mainland are shallow lagoons with lush seagrass and hard-bottom communities of sponges and isolated corals. Along the east coast of the mainland there is a narrow band of mangroves.

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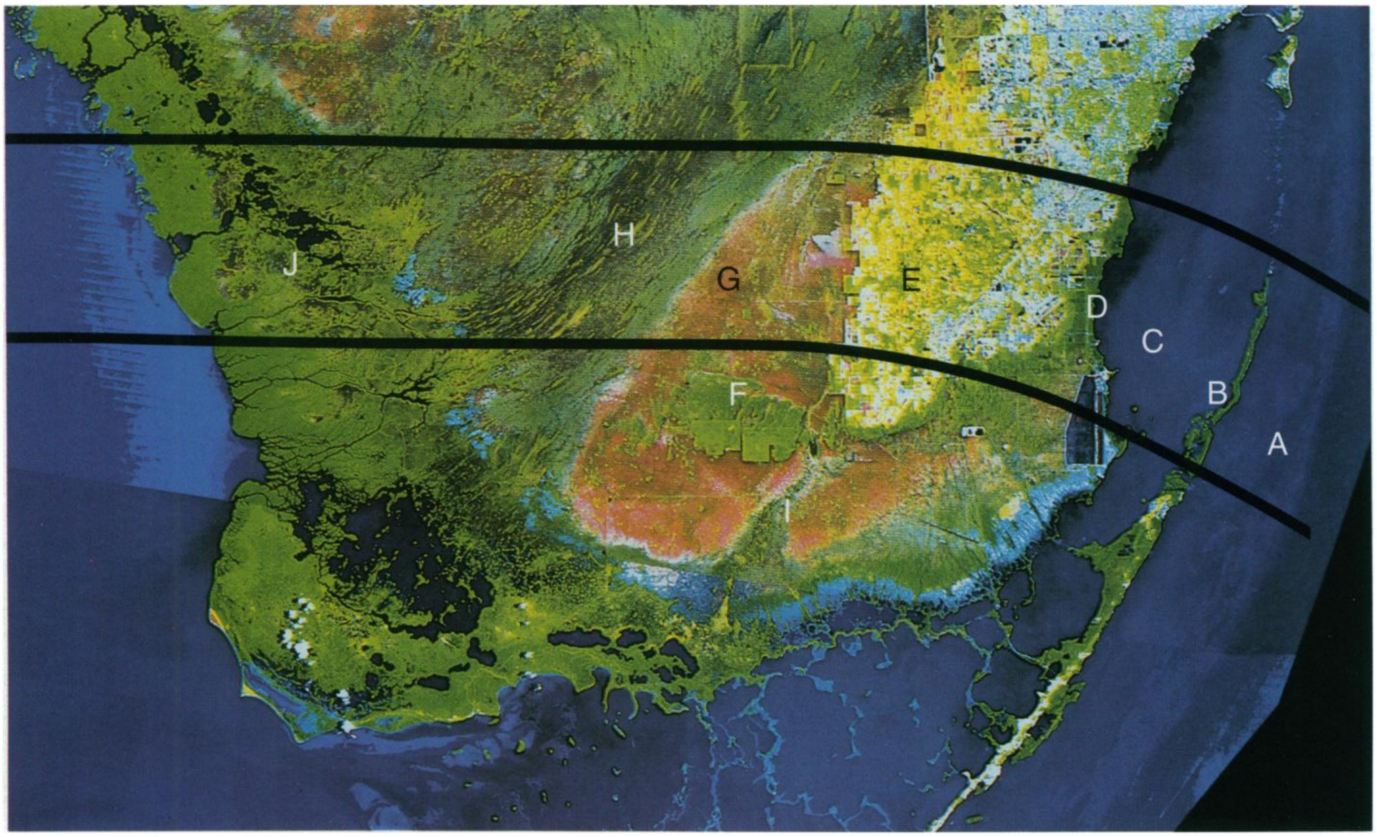


Figure 1. South Florida as a false-color image and the path of the eye of Hurricane Andrew. The storm wall extended to the south and to the north for approximately half the width of the path of the eye. The strongest winds were south and especially east of the eye (that is, within the eye's path after it had passed over). Winds were stronger as the storm wall reached land (0830 UTC, 0430 local time) than when it left it (nearly 4 hr later). Offshore, A, the water depth increases rapidly beyond a fringing coral reef, which shows as a lighter blue. The first land Andrew crossed was mangrove-covered islands—keys, B, behind which are shallow bays, C, and a narrow strip of mangroves, D. It then passed over populated areas, including Homestead, E, and north of Long Pine Key, F, an upland area dominated by pine forest and abandoned agricultural land, much of it invaded by *Schinus*. It then crossed short-hydroperiod marshes, G, which appear pink to red. Shark River Slough, a long-hydroperiod marsh, G, appears brownish, with the hammocks and bayheads visible as long, green islands. (These are more obvious north of the storm's eye.) Taylor Slough, I, was south of the eye's path. Finally, the storm crossed an extensive belt of mangroves, J, which show as uniform bright green, and a complex network of waterways (very dark blue). This mangrove and open saltwater complex stretches to the south and east, encompassing Whitewater Bay and Cape Sable. The mangrove belt narrows east of Taylor Slough. Image: Brent Moll, South Florida Management District.

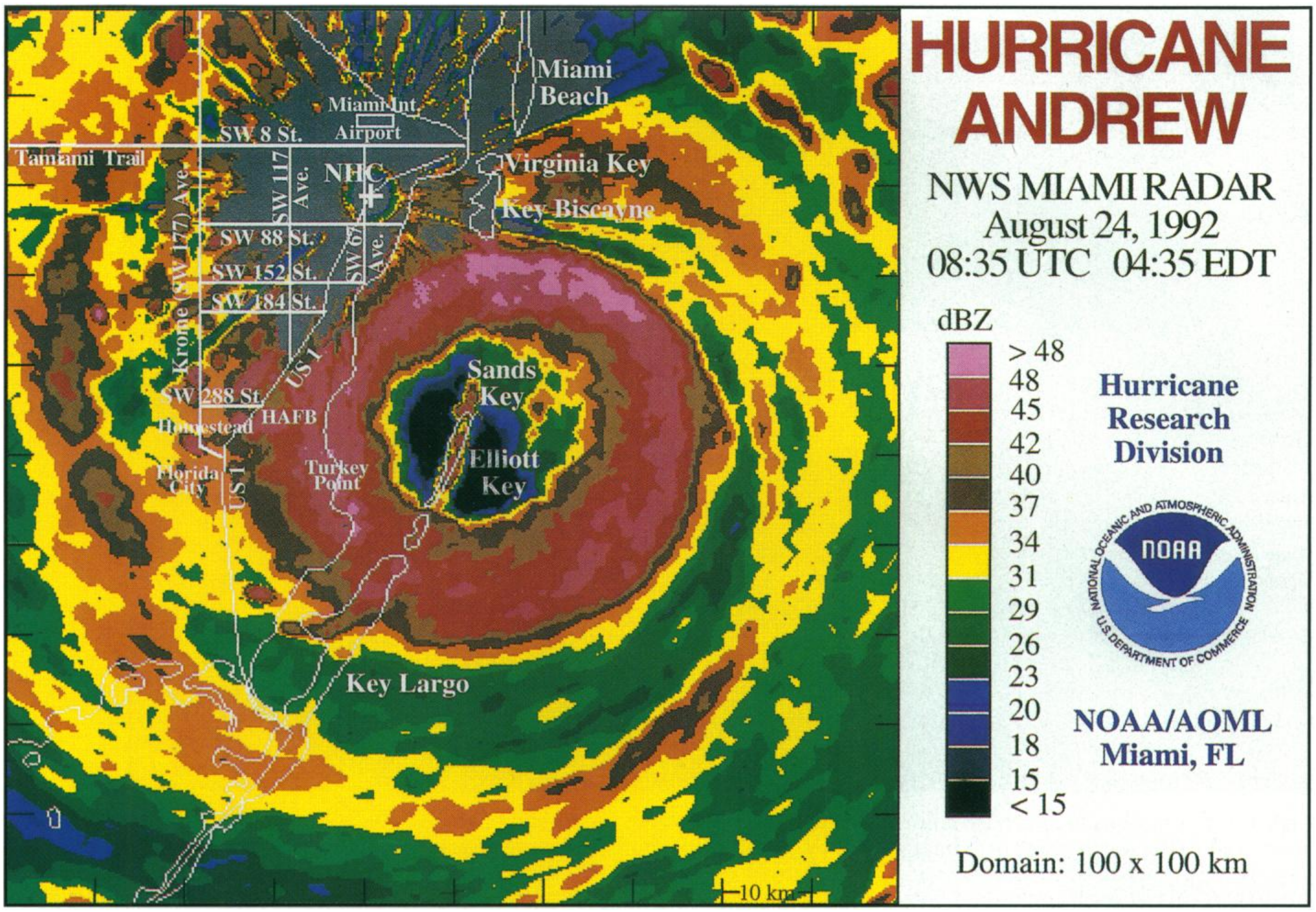
The upland areas are also diverse. There are open, fire-adapted pine-dominated forests and dense, tropical broad-leaved hardwood forests within Everglades National Park. Cypress-dominated forests are the most widespread vegetation type in Big Cypress National Preserve and a minor component in Everglades National Park. There are also bayheads—low, closed-canopy forests that grow as forest islands in areas flooded up to 6 months each year.

Moving inland, the Everglades are an almost-flat expanse of seasonal freshwater marshes dotted with tall forest islands (called hammocks) and bayheads. Thunderstorms feed the highest water levels, which last from May to October. Historically, these marshes were also fed by a slow southward movement of water from Lake Okeechobee towards Florida Bay. However, the marshes no longer enjoy a natural water flow. An elaborate network of canals and levees from Lake Okeechobee southward to Everglades National Park now controls the timing and amount of the water flow in a pattern unrelated to the historical flow.

Even the deepest channels of the marshes, Shark River and Taylor Sloughs, are relatively broad and shallow. (The locations mentioned in this and the four articles that follow are provided in Figure 2, page 228.) As the marshes dry, from November to April, these sloughs retain water longest. The length of inundation, or hydroperiod, plays a major role in determining the ecological communities that develop.

The west coast, like the east coast, has extensive mangrove forests interspersed with interconnecting waterways and shallow bays. It has no off-shore reef communities.

How these ecosystems fared during and immediately after Hurricane Andrew is the subject of each of these four articles. We provide an overview of the changes and consider how quickly the ecosystems are likely to recover. Indeed, will the ecosystems recover at all? Certainly, the ecosystems of South Florida have experienced hurricanes frequently in their history. As hu-



The weather radar measures the power from the portion of the radar beams scattered by raindrops and ice particles. The higher values of dBZ correspond to areas with larger amounts of rain; these areas typically have stronger winds.

man encroachment advances, these ecosystems are becoming geographically much smaller and are becoming subjected to a wide range of anthropogenic stresses. Do these changes leave the ecosystems more vulnerable to future hurricanes, fires, droughts, freezes, or external development pressures?

The initial assessment

Marine environments. Tilmant et al. (page 230 this issue) found that the major storm effects were changes in the nearshore water quality, localized intense bottom scouring, and beach overwash. The stirring of sediments increased the dissolved phosphate levels, leading to plankton blooms and low oxygen levels. In hard-bottom communities, sponges, corals, and sea whips were sheared from their substrate and deposited among extensive wracks of debris. The juvenile spiny lobsters normally found under sponges and corals in central Biscayne Bay disappeared. On some reefs, the storm scoured the tops, rolling over the 200 year-old coral heads and breaking off branching corals. The seagrass beds, in contrast, appeared little affected.

Three of the most conspicuous vertebrates also appeared to have suffered little mortality. R. W. Snow of the South Florida Research Center of the Everglades National Park in Homestead, Florida, does regular aerial surveys of the manatees. Immediately after the storm, he counted more than on any previous census. Sea turtle nesting sites were likely to have been improved by the overwash of seawater and the newly deposited sand, and the crocodile nesting beaches were unaffected because they are located south of the storm's effects.

Uplands. Loope et al. (page 238 this issue) report that the most dramatic effect of the storm was the structural damage to trees. In the hammocks within the storm's path, most of the large hardwood trees were defoliated. Between 20% and 30% of the trees were uprooted, had broken trunks, or had lost major limbs. From 25% to 40% of the pines were toppled or broken. Cypress trees fared much better and often held their needles.

The parks' terrestrial vertebrates contain several endangered species and other taxonomic groups that scientists monitor closely. There were few examples of direct mortality. All the radiotagged Florida panthers survived the storm, as did radiotagged black bears, white-tailed deer, and snail kites. (The panther and kite are endangered species.) Nearly all the nesting trees of the endangered red-cockaded woodpecker fell; we do not know the fate of the birds themselves. The swallow-tailed kite, a migrant that has an important population in the area, was absent when the storm hit. This species, like the red-cockaded woodpecker, may have lost nesting sites. We know little of the storm's effects on invertebrates.

Freshwater marshes. Compared with the obvious damage to hardwood hammocks and mangroves (see below), the freshwater marshes appeared little affected. Roman et al. (page 247 this issue) argue that these superficial appearances may be misleading. Under normal conditions, there is an extensive periphyton—a golden-brown algal mat that locally coats the marsh. The periphyton provides a habitat important to the marshes' food chains. The storm removed the periphyton, piling debris into windrows. Perhaps as a result, fish abundance declined by an order of magnitude at several monitoring stations.

The marsh's most conspicuous vertebrate, the alligator, appeared to have suffered little immediate mortality, though some nests were destroyed. The Cape Sable sparrow, an endangered species, is so secretive that its numbers had to wait until the breeding season of 1993 for estimation. The population west of Shark River Slough was in the storm's eye and declined dramatically from 1992 to 1993.[1] Although other factors cannot be excluded, Andrew may have reduced the sparrow's total numbers from approximately 6000 to 4000. Analysis of long-term, monthly counts of egrets, herons, and ibis showed few changes, though many of their roosting sites were destroyed. The greatest number of dead birds observed directly was approximately 200 white ibis and egret corpses at a roost in Biscayne Bay.

The small extent of the losses may have been a result of good luck. In addition to high winds, in previous hurricanes (see page 261 this issue) storm surges inundated large areas with saltwater that killed many marsh animals and plants. The east coat is relatively high, so Andrew's due westerly path could not push saltwater far inland. Consequently, many crucial areas were not thus flooded. In addition, Andrew's unusually low amount of rain limited the freshwater flooding.

Mangroves. Two weeks after the storm, an overhead view of the mangroves had many areas resembling that of a deciduous forest in winter. The grayish brown of the completely defoliated area made a sharp boundary with the intense greens of the area outside the storm's path (see photo page 257 this issue).

Smith et al. (page 256 this issue) found that at Highland Beach, where the hurricane's eye left the west coast to move across the gulf, more than 85% of the mangrove trees had blown over. On-ground inspections showed that many of the standing trees had cracked trunks. This observation, and experience with other hurricanes (Whigham et al. 1991), suggests that trees will continue to die for a year or more.

Will the ecosystems recover?

The answer is a guarded yes. We may think of hurricanes as once-in-a-lifetime events, but to a tree they are not. We expect hurricanes repeatedly, if erratically, within an individual hammock tree's or coral head's lifetime. The Caribbean as a whole averages more than four hurricanes per year (Walker et al. 1991a). Fifteen hurricanes have crossed Puerto Rico in less than 300 years (Scatena and Larson 1991). The paths of many hurricanes, including Donna (1960), Betsy (1965), and Andrew (1992), have traversed the three South Florida parks this century (see page 261 this issue).

Hurricanes have been a central feature in evolution of subtropical Caribbean ecosystems. They are widespread and unavoidable in the long term and, indeed, such disturbances may be integral to the development of these ecosystems.

From Hurricane Andrew, probably because of the storm's rapid transit, the damage to the coral reefs and marsh ecosystems was less than that caused by other Caribbean storms. The marine and freshwater teams (Tilmant et al. page 230 and Roman et al. page 247 this issue) viewed the hurricane's effects as consistent with the usual patterns ecosystem growth and disturbance.

Although harder hit initially, the forest ecosystems may be as resilient as the marshes and marine environments. Only 16% of wind-thrown trees and 29% of broken trees died within two years after hurricane Gilbert (Whigham et al. 1991). That hurricane hit the Yucatan Peninsula with greater ferocity than Andrew, clocking winds of 300 km/hr. By extension, many of trees seriously injured in 1992 should survive. Indeed, within three weeks of Andrew, many of the tropical hardwoods were already releafing. It looked as if spring had come to the forests in September.

Reinforcing this optimism about the park areas' fate is the knowledge that some species were not seriously affected by the storm. For example, we know from routine counts that manatee and wading bird numbers hardly changed (see Tilmant et al. page 230 and Roman et al. page 247 this issue). There are not merely before-and-after counts, but counts taken frequently for many years. They demonstrate the normal variation in population numbers within and between years. The existence of long-term study plots on the coral reefs off Key Biscayne greatly aided the assessments of damage to marine communities (see Tilmant et al. page 230 this issue). Similarly, long-term water quality data for the interior Everglades allowed conclusions about the storm's effects (see Roman et al. page 247 this issue).

The caveats. All three teams shared the same two concerns that temper the optimism just expressed. First, there are important gaps in the long-term data, gaps that often reflect our predilection for large, warm-blooded vertebrates. Invertebrates and fishes get short shrift. As a result, we are much less certain about the changes in the marshes—the effects of the loss of periphyton, for example—than in the forests. In addition, too few permanent vegetation plots have been established with the expectation of repeated inventories made routinely over decades to centuries.

Certainly, readily countable birds

[1]O. L. Bass, 1993, personal communication. South Florida Reesearch Center, Everglades National Park.

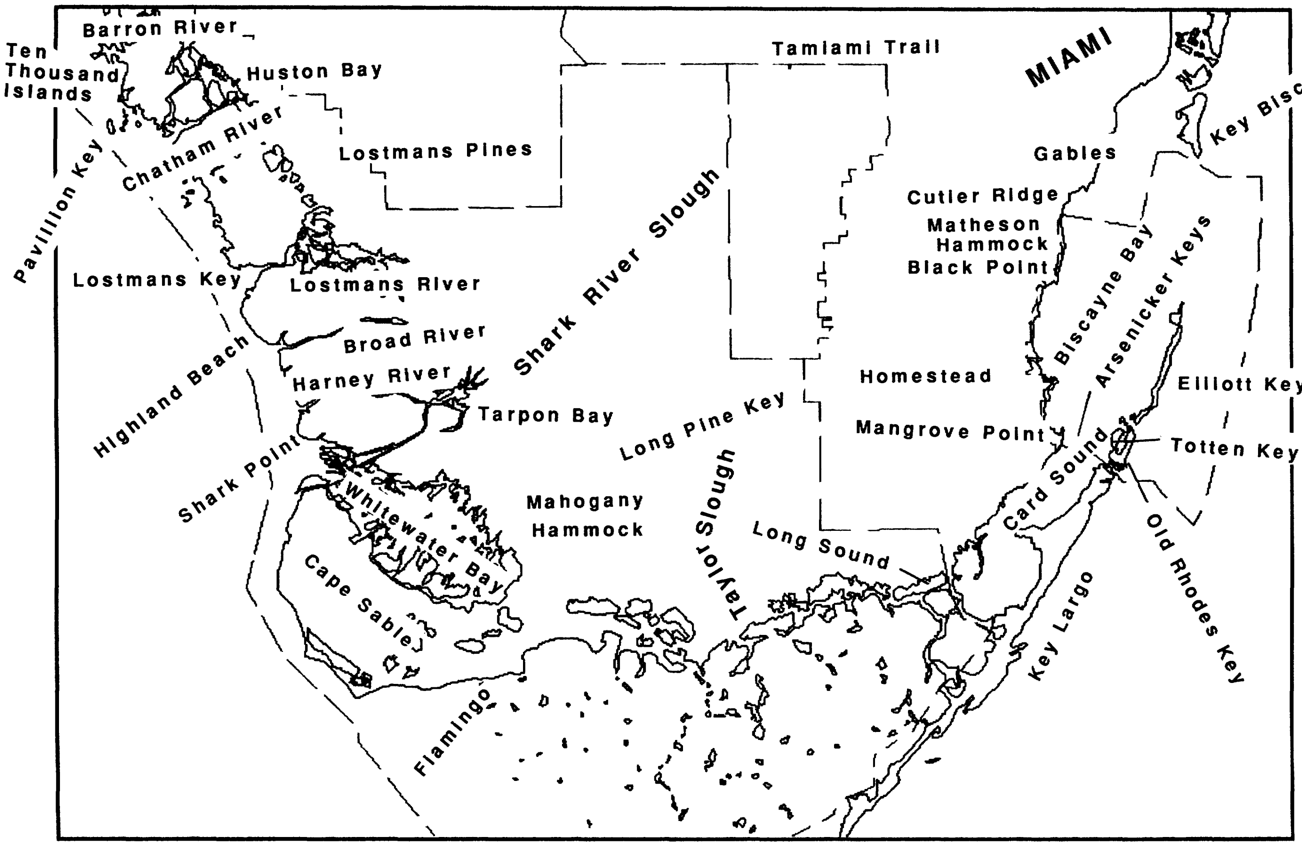


Figure 2. A map of South Florida, showing the places named in this article and the four articles that follow.

and mammals facilitate monitoring. Although it is easier to count panthers, wading birds, and manatees than their food supplies, this selection may miss important processes. Changes in wading bird populations may not follow changes in fish populations but may, for example, be driven principally by access to the fish. Access probably depends on the dependable drying of the marshes and thus on water flows (Fleming et al. in press a,b).

Some habitats and their constituents have been neglected by those who instigate regular counts. The short-hydroperiod marshes are the home of the endangered Cape Sable sparrow. Yet, this species, one of the rarest birds in the eastern United States, was counted only for the second time in the summer before Andrew.

The second, and by far the most serious concern, is our limited understanding of the ability of the ecosystems to recover naturally. There are two sides to this concern.

The first side is that all three parks are but fragments of the once-extensive ecosystems they represent. Nowhere is this issue of scale more obvious than with the various endangered species. By good fortune, Andrew caused little flooding. The eye of the storm went north of some species (e.g., the crocodile), south of others (e.g., the snail kite), and the storm occurred when other species were absent (e.g., the swallow-tailed kite).

Next time, we might not be so lucky, for there is no typical hurricane. Comparative studies of hurricanes (e.g., Walker et al. 1991b) show important differences. Andrew was relatively dry, fast-moving, of small diameter, caused little saltwater incursion, and was not followed by fires. Other Florida hurricanes (see Smith et al. page 256 this issue) have been wetter, slower-moving, have damaged vegetation on a wider path, and inundated larger areas with saltwater. The fires that followed hurricane Gilbert in Yucatan killed more trees than did the storm itself (see Loope et al. page 238 this issue).

If luck runs out, small but crucial numbers of panthers, snail kites, or other species may be killed. Historically, these species would have been neither rare nor so local. Rare, local populations often do not survive the loss of even small numbers. Parks and other protected areas may be large enough to protect populations under normal year-to-year changes. But, in the long run, are they large enough to survive the infrequent, natural, but highly variable disturbance that hurricanes typify?

The second side of the concern about ecosystems' ability to recover is that all three parks in South Florida are under continuous threat from a wide variety of anthropogenic factors. Marine communities must experience hurricanes from time to time, but they have not adapted to withstand the discharge of fuel oil that spewed from damaged boats in Biscayne Bay and adjacent marinas (see Tilmant et al. page 230 this issue); the discharge continued for at least four weeks after the storm. The marine team found that the most severe reef damage came from human debris such as lobster and crab traps that smashed corals and reefs. And as the storm moved into the Biscayne National Park, it broke a ship sunk as an artificial reef at a depth of 23 m and impaled it on natural reefs.

The storm created more than 2×10^7 cubic meters of debris, approximately three quarters of which was trees and shrubs (NPS 1991), a volume six times that of the great pyramid at Giza. The normal process would be for the woody detritus to break down naturally. But outside the parks, material was burned, and the emissions blew over Everglades National Park. What was not burned was buried and could create problems if toxins leach into ground water that then enters the park.

The water flows in South Florida are no longer natural ones (see Roman et al. page 247 this issue), and the altered flows create problems and controversy even in normal times (Orians et al. 1992). Andrew damaged water-control structures, increasing the eastward flow of water at the expense of the more natural southward flow into Florida Bay. This change threatened to dry the marshes prematurely and increase already high salinities in Florida Bay still further.

Nor are the terrestrial systems completely natural. Nonnative plants have spread across large areas of South Florida and are a major concern (see Loope et al. page 238 this issue). Hurricane Donna spread seeds of the Australian tree *Casuarina* up the west coast of Everglades National Park in 1960. The resulting trees posed a sufficient threat to turtle nesting areas to prompt an active tree-removal program. The Brazilian pepper, *Schinus terebinthifolius*, was introduced in the late nineteenth century and is now found across 39,000 hectares of Everglades National Park. When hurricanes create open patches, particularly in the mangrove forests, *Schinus* soon dominates these local habitats, perhaps because it can often occupy openings more quickly than can the native mangroves. Another threat may be the Australian tree *Melaleuca quinquenervia*. Introduced in the 1920s to dry the marshes, it dominates large areas of the water conservation areas to the north of the Park. Simply put, the hurricane may tip the balance in favor of these alien species and have long-lasting effects.

A ten-day study cannot fully evaluate such threats. It will take an appreciation of what the possible threats are, plus constant vigilance. Such vigilance requires more long-term monitoring. In our experience, long-term studies, particularly long-term monitoring, are often hard to fund. Yet, the existence of marine, freshwater, and upland monitoring allows Andrew's immediate and long-term effects to be known in unusual detail.

Chance, in Andrew's form, came to a well-prepared group of scientists in South Florida. As a result, we may learn much both about hurricanes and about the workings of several different ecosystems. There is still important information that we do not have about Andrew's effects and many gaps in the monitoring. The problem of insuffcient background information extends to other national parks (NRC 1992) and ecosystems generally (Likens 1987, NRC 1990, *BioScience* special issue July 1990). Only continued monitoring will allow modeling and then testing of speculations about the long-term consequences of ecosystem fragmentation, alien plants, the full range of external threats, and natural episodic events.

Acknowledgments

This article is based on the four articles that follow, the report of the assessment team to the National Park service, and our own observations. It is authored by the coordinator of this special *BioScience* issue (SLP), the assessment leader (GED), and the three team leaders (listed in alphabetical order). The individual team members authored the articles that follow; their contributions were crucial to this introductory article as well. In addition to the acknowledgments given in the individual articles, SLP thanks the National Park Service for the opportunity to participate in the assessment and recovery planning after Hurricane Andrew. In particular, he thanks Marty Fleming and Michael Soukup for the invitation to visit Everglades National Park in the immediate aftermath of the storm and for the logistical support they provided. His wife, Julia, helped collect data and endured hours in a helicopter with equanimity.

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